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THE EFFECT OF AIR QUALITY ON SLEEP

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SUMMARY

The effect of air quality on sleep was examined for occupants of 14 identical single-occupancy dormitory rooms. The subjects, half women, were exposed to two conditions (open/closed window), each for one week, resulting in night-time average CO₂ levels of 660 and 2585 ppm, and air temperatures of 24.7 and 23.9°C, respectively. Sleep was assessed from movement data recorded on wristwatch-type actigraphs and from online morning questionnaires, including the Groningen Sleep Quality scale, questions about the sleep environment, next-day well-being, SBS symptoms, and two tests of mental performance. Although no significant effects on the sleep quality scale or on next-day performance could be shown, there were significant and positive effects of a higher ventilation rate (open window) on the actigraph measured sleep latency and on the subjects' assessment of the freshness of the air, their ability to fall asleep and nasal dryness. There was a negative effect on reported lip dryness.

INTRODUCTION

Sleep is essential for a person's health and well-being. In studies conducted among Finnish (Tynjälä et al., 1999) and Dutch children (Meijer et al., 2000), a strong correlation between sleep quality and their concentration the next day was found. Both studies show that good and refreshing sleep is one of the constituents for general well-being among adolescents. Many factors are thought to influence sleep quality, among those the indoor environmental quality (IEQ) parameters which include: air temperature and relative humidity, air velocity, particulate matter concentration, illumination level, sound level and ventilation rate. The effect of air quality was investigated in the present study.

Only a few field studies of sleep as a function of indoor air quality have been carried out. A study of typical Belgian houses by Laverge and Janssens (2011a) estimated that exposure to poor air quality is up to 16 times higher in the bedroom. Laverge and Janssens (2011b) then asked 10 students to sleep in their dormitories for one month, in periods with open window (high ventilation rate) and with closed window (low ventilation rate). CO₂ concentration, air temperature and relative humidity were measured throughout. The sleep pattern of the subjects was measured using actigraphy, and the subjects completed a questionnaire every morning to report their sleep quality. As usable data was obtained from only 6 subjects there were no significant effects of the intervention, although sleep efficiency (proportion of time in

bed spent asleep) tended to be less when windows were open. The objective of the present study was to investigate the effect of open windows on indoor air quality, sleep quality and next-day well-being.

METHODS

Facilities and subjects

The experiment took place in the Campus Village at the Technical University of Denmark (DTU), 10 km north of Copenhagen. This housing complex for international students consists of twenty identical units, each housing up to ten students. All rooms are identical (3.6 m in length, 3.0 m in width and 2.4 m in height) with one double-framed window located opposite the door. An air vent placed in the outer wall was sealed during the experiment. Each housing complex unit includes common toilet, bath and kitchen facilities with mechanical exhaust, creating a negative pressure in the corridor. The rooms are furnished with a sofa/bed, a wardrobe, a desk, and sometimes additional private furniture.

Twenty of the occupants participated in the study, but data from 6 subjects was omitted from the analysis after it was determined that a leaking air seal had affected the physical conditions to which some of the subjects were exposed and because insufficient data had been obtained from some other subjects.

The remaining 14 subjects originated from 10 nations, with an equal number of males and females. Each subject was exposed to two experimental conditions, open and closed window, in a balanced order of exposure, each condition lasting one week. In the “open window condition” the one window sash was held open by a 10 cm long plastic window stay. In the daytime the subjects were allowed to close or open the window according to their preferences. They were asked to adjust the electric heater below the window to achieve their preferred thermal condition for sleeping in both conditions, and to maintain their normal life style, although with restricted alcohol and caffeine consumption. The experiment was performed from Saturday the 22nd of September to Saturday the 8th of December 2012 with outdoor temperatures between -7°C and 11°C at night. The experimental condition in the rooms was changed on Saturdays. Only data from the four nights between Monday and Friday were used in the subsequent data analysis.

Physical measurements and questionnaires

During the experimental period the air temperature, relative humidity and CO₂ concentration were measured at 5-minute intervals. Two measuring stations were used, one in the centre of each side wall. A HOBO U12-012 data logger was used to measure air temperature and relative humidity with an accuracy of ± 0.35 K and $\pm 2.5\%$, respectively. A Vaisala GM20 CO₂ sensor, calibrated for the range 0-5000 ppm, was used to measure the CO₂ levels with an accuracy of $\pm (2\% \text{ of range} + 2\% \text{ of reading})$.

The activity of the subjects was recorded each minute for two weeks using an actigraph. The Philips Actiwatch 2 (Figure 1) is a small, actigraphy data logger designed for



Figure 1. Philips Actiwatch 2.

clinical and scientific use. It records a measure of gross motor activity that can be used to visualise rest activity patterns and quantify physical activity. Actigraphy is a well-established method for field studies of sleep (Kushida et al., 2001).

As part of a screening process, the subjects were asked to fill in a recruitment questionnaire and a background questionnaire, which made it possible to exclude people suffering from asthma, allergy, sensitive skin or sleeping disorders, and people smoking or using medication. The background questionnaire was based on the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989), which contains questions about sleeping habits during the past month.

Every morning the subjects were asked to fill in an on-line questionnaire no later than 10 minutes after waking up. It consisted of questions about sleep quality, sleep environment, SBS symptoms, sleep symptoms and well-being the previous day. Two on-line performance tests were applied, a Grammatical Reasoning Test (Baddeley, 1968) and the Tsai-Partington Numbers Test (Ammons, 1955), the latter with the modifications introduced by Wyon (1969). The questionnaire included fifteen questions from the Groningen Sleep Quality (GSQ) Scale (Mulder Hajonides et al., 1980) which were to be marked true or false. It also included visual-analogue scales rating 7 aspects of the sleep environment, 13 SBS symptoms, 4 aspects of sleep quality and 2 next-day symptoms. Additional questions were about clothing worn during sleep, reasons for any awakenings, how many times the subjects woke up or got out of bed, and what time they went to bed and woke up.

Data processing and statistical analysis

All of the physical measurements of air temperature, relative humidity and CO₂ concentration can be assumed to be Normally distributed, so they were registered as average, minimum, maximum and standard deviation values. The data from the online morning questionnaire were tested for Normality using the Shapiro-Wilks Test. Data from the Tsai-Partington Numbers Test, Baddeley's Reasoning Test, and the actiwatches were not Normally distributed. The pair-wise differences between the two conditions were tested using the non-parametric Wilcoxon Matched-Pair Signed-Ranks Test. The P-values reported in the Results section are for a 2-tailed test of the difference between conditions of the 4-day mean values.

RESULTS AND DISCUSSION

Physical measurements of the indoor environment

The average night-time **air temperature** in the 14 rooms was 23.9°C in the closed window condition and 24.7°C in the open window condition. There were considerable differences between individual subjects, with a minimum average value of 16.3°C and a maximum of 27.8°C. The temperature was on average 1.6 K higher in the open window condition for 10 of the 14 subjects, and 1.4 K lower for the remaining 4 subjects. The female subjects were on average exposed to a 3 K higher temperature than the male subjects.

The night-time average values of **relative humidity** for each subject were in the range between 40% to 72% for the closed window condition and 23% to 64% for the open window condition, all subjects experiencing lower humidity with an open window. The average with closed window was 54%, and 40% with open window.

Average night-time values of the **CO₂ concentration** in the 14 rooms during the experiment are shown in Figure 2, documenting the large effect of the intervention. The average values of CO₂ concentration were between 1730 ppm to 3900 ppm for the closed window condition and 525 ppm to 840 ppm when the window was open. The average CO₂ concentration was 2585 ppm in the closed window condition and 660 ppm in the open window condition, corresponding to a difference of 8-9 times in air exchange rate. The CO₂ concentration in an occupied room is a good indicator of the air change rate, and thus of changes in the concentration of pollutants originating from other sources, e.g. building materials. In an 11 m² single-occupied bedroom, classed in Europe as a bedroom with low occupant density, the measured values for the closed window condition are considered unacceptable, although they are not unusual. Studies including 500 Danish children (Bekö et al., 2010) showed that 57% of the bedrooms did not fulfil the minimum ventilation requirements stipulated in EN 15251 (2007).

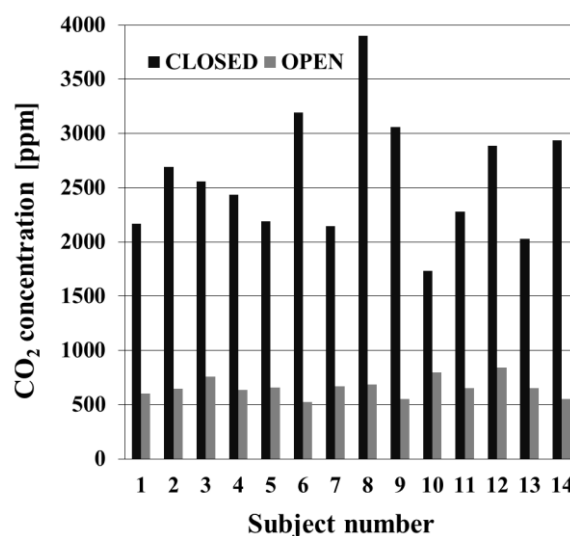


Figure 2. Comparison of the CO₂ concentration during night-time, each bar representing a 4-day average.

Morning questionnaire

Table 1 shows the results from the Wilcoxon Signed-Rank Test providing P-values for two-tailed tests with statistically significant differences ($P < 0.05$) shown in bold.

Table 1. Results from the statistical analysis of the morning questionnaire with P-values from the Wilcoxon Signed-Rank Test.

Variable	P-value	Comments	Variable	P-value	Comments
GSQ SCALE			SBS SYMPTOMS		
Score	0.1080	Better when open	Nasal dryness	0.0480	Less dry when open
SLEEP ENVIRONMENT			Nose blocked	0.4899	
Temperature	0.2209		Mouth dryness	0.2859	
Air humidity	0.7299		Skin dryness	0.0869	More dry when open
Freshness of air	0.0010	More fresh when open	Eye dryness	0.3003	
Air movement	0.0555	More movement when open	Eye clearness	0.2634	
Noise	0.2585		Lip dryness	0.0413	More dry when open
Illumination	0.7776		Thirst	0.9750	
Isolation of cover	0.2455		Headache	0.6496	
SLEEP SYMPTOMS			Mental state	0.7776	
Quality of sleep	0.8753		Alertness	0.9250	
Duration of sleep	0.8753		Rested	0.9250	
Lightness of sleep	0.5936		Wellbeing	0.9165	
Ability to fall asleep	0.0303	Better ability when open	BADDELEY'S TEST		
NEXT-DAY SYMPTOMS			Score	0.1579	
Sleepiness	0.0516	Less sleepy when open	TSAT-PARTINGTON TEST		
Ability to concentrate	0.0806	Better ability when open	Score	0.4216	

All P-values are 2-tailed. Bold: $P < 0.05$.

Results for some of the variables are presented graphically as quartiles in Figures 3-11. Each box represents the interquartile range, and the horizontal line dividing the box is the median.

The difference between conditions on the **Groningen Sleep Quality (GSQ) Scale** did not reach significance ($P < 0.1078$), although there was a tendency for subjects to report sleeping better, not worse, with the window open (Figure 3). It should be recalled that the (non-significant) tendency noted by Laverge and Janssens (2011b, op. cit.) was in the opposite direction.

In the **Sleep environment** section, the results show a significant difference ($P < 0.0010$) for **Freshness of air** (Figure 4). The subjects reported the air to be fresher in the open window condition, as expected, since the experiment took place in a residential area away from possible sources of outdoor pollution. **Air movement** was not reported significantly differently ($P < 0.0555$), although there was an almost significant tendency for the subjects to report more air movement with the window open (Figure 5). A difference might have been expected for **Noise**, but the subjects did not find the environment to be any noisier in the open window condition, probably because internal noise from other students dominated in a quiet neighbourhood.

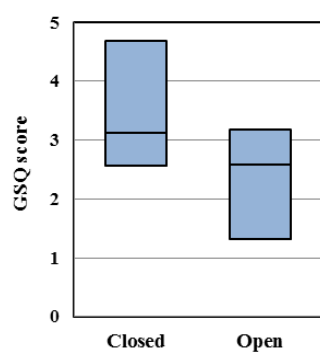


Figure 3. Score from the GSQ scale.

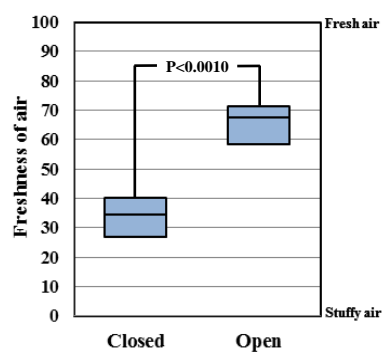


Figure 4. Ratings of freshness of air.

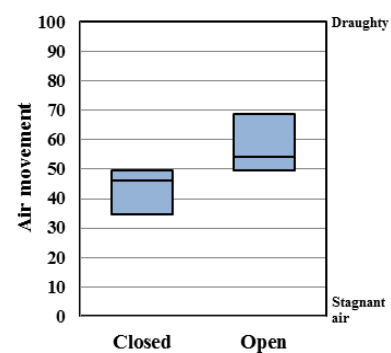


Figure 5. Ratings of air movement.

In the **Sleep symptoms** section a significant difference was found only for **Ability to fall asleep** ($P < 0.0303$). The subjects reported that it was easier to fall asleep in the open window condition (Figure 6).

The statistical analysis of **Next-day symptoms** did not show significant differences, but there was an almost significant tendency for the subjects to feel less sleepy ($P < 0.0516$) and to have a greater ability to concentrate ($P < 0.0806$) the day after sleeping with open window (Figures 7 and 8).

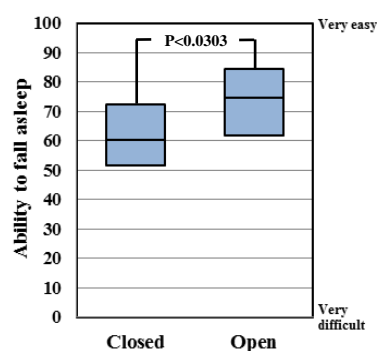


Figure 6. Ratings of ability to fall asleep.

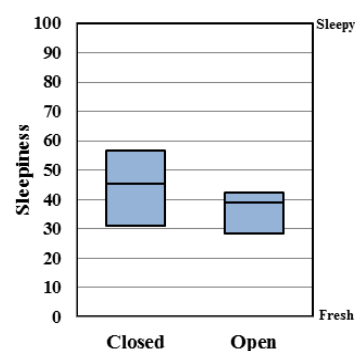


Figure 7. Ratings of sleepiness.

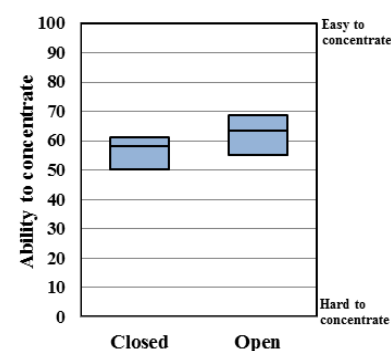


Figure 8. Ratings of ability to concentrate.

From the statistical analysis of the assessments of the 13 **SBS symptoms**, there was found a statistically significant difference between the two conditions for **Nasal dryness** ($P<0.0480$) and **Lip dryness** ($P<0.0413$), see Figures 9 and 10. The subjects felt their nose to be less dry but their lips to be drier with the window open. Although not statistically significant ($P<0.0869$), there was a tendency for more **Skin dryness** in the open window condition (Figure 11). Drier lips and skin in the open window condition may be due to the lower relative humidity in this condition. The more pronounced nasal dryness in the condition with closed window could be caused by the higher concentration of pollutants due to the low air exchange rate. Field investigations by Sundell and Lindvall (1993) concluded that the indoor air humidity is not an important factor for the sensation of dryness that might be caused by pollutants in the air. Results from laboratory experiments performed by Fang et al. (2004) appear to agree that indoor air pollutants may contribute to symptoms that are similar to the sensation of dryness.

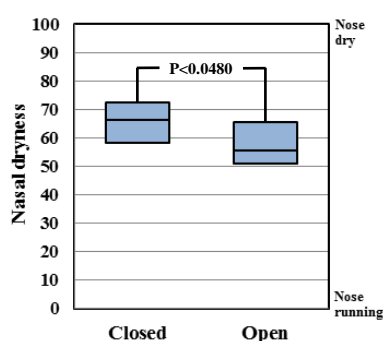


Figure 9. Ratings of nasal dryness.

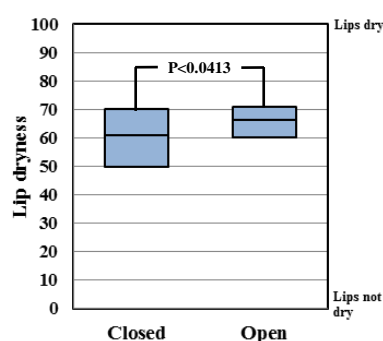


Figure 10. Ratings of lip dryness.

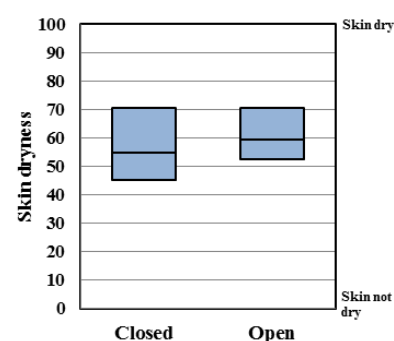


Figure 11. Ratings of skin dryness.

There were no significant effects of the intervention on **Baddeley's Grammatical Reasoning Test** or the **Tsai-Partington Test**, and no trends were apparent in the quartile graphs (not shown).

Actigraph data

The results from the statistical analysis of the actigraph data are shown in Table 2, where sleep duration is the time spent sleeping, excluding intervening periods spent awake; sleep latency is the time required to fall asleep; snooze time is the time required to become active after finally awakening; sleep efficiency is the percentage of time in bed spent asleep.

Table 2. P-values obtained from the Wilcoxon Signed-Rank Test for the actigraph data.

Variable	P-value	Comments
ACTIWATCH DATA		
Sleep duration	0.5098	
Sleep latency	0.0480	Shorter when open
Snooze time	0.4899	
Sleep efficiency	0.0736	Efficient when open
No. of awakenings	0.9750	

All P-values are 2-tailed. Bold: $P<0.05$.

The results show a significant improvement in **Sleep latency** ($P<0.0480$) in the open window condition, which leads to a positive tendency for **Sleep efficiency** ($P<0.0736$) since more time is left for sleeping. The result for sleep latency is in agreement with the subjects' own assessment of their ability to fall asleep. The process of falling asleep occurs as body metabolism and central body temperatures are both reduced. For the latter to happen, the body must lose stored heat. Increased air movement and lower RH make this easier to achieve, by

increasing evaporation from exposed skin, especially facial skin. This is a possible mechanism for the observed and reported decrease in sleep latency.

Having established both subjectively and objectively that sleep latency was reduced by having the window open, it is reasonable to expect less sleepiness and better ability to concentrate after a night with better sleep. It is then appropriate to use a 1-tail P-value as an estimate of the probability of the observed change, in which case a significant improvement was found both for sleepiness ($P < 0.0258$) and ability to concentrate ($P < 0.0403$) the day after sleeping with the window open.

Experimental design

The study was performed in the homes of the subjects, in their normal sleeping environment. This was made possible by using actigraphy and online questionnaires. Although this added to the realism of the study, the physical parameters of the sleep environment were not controlled and the subjects were not blinded to the intervention. Confounding occurred because opening a window affects the relative humidity and the air movement as well as the air quality. This study was of the effects of a simple intervention, one that can be made in most bedrooms, namely opening a window.

The subjects were half men, half women, coming from 10 different countries and 3 different continents, which makes the results more generally applicable. The probability of obtaining statistically significant results would probably have been increased by using a less diverse group of subjects and by increasing the number of subjects.

The use of identical student dormitory rooms reduced the number of other confounding variables such as the outdoor noise level, and indoor and outdoor pollution sources. The rooms are designed for single occupancy so there was no disturbance from other people in the room. However, the student lifestyle, with no regular schedule during the week will have increased individual variation and thus reduced the probability of obtaining significant results.

CONCLUSIONS

The physical measurements of the indoor environment showed a marked difference between the two conditions. The average CO₂ concentrations were 2585 ppm in the closed window condition and 660 ppm in the open window condition, with only minor differences for the measured temperature, so the objective of the present study was achieved.

The intervention of opening the window had a significant positive effect on the assessed freshness of air. The lower relative humidity in the open window condition resulted in more lip and skin dryness, but there was less nasal dryness, possibly because the concentration of all airborne pollutants was reduced.

The subjectively assessed ability to fall asleep was significantly greater in the open window condition, a result supported by the actigraphy data. The Groningen Sleep Quality Scale showed a tendency for the subjects to sleep better with the window open. Subjects reported feeling less sleepy and being better able to concentrate the day after sleeping with the window open.

ACKNOWLEDGEMENT

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